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Measurement of the integrated luminosities of the data taken by BESⅢ at $\sqrt{s}$=3.650 and 3.773 GeV*

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Abstract: Data sets were collected with the BESIII detector at the BEPCII collider at the center-of-mass energy of $\sqrt{s}$=3.650 GeV during May 2009 and at $\sqrt{s}$=3.773 GeV from January 2010 to May 2011. By analyzing the large angle Bhabha scattering events, the integrated luminosities of the two data sets are measured to be (44.49±0.02±0.44) pb^{-1} and (2916.94±0.18±29.17) pb^{-1}, respectively, where the first error is statistical and the second error is systematic.

Key words: Bhabha scattering events, integrated luminosity, cross section

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1 Introduction

In e^+e^- collider experiments, the number of events for $e^+e^-\to X$ observed in a data set can be written as

$$N^{\rm obs}_{e^+e^-\to X}(\sqrt{s})=L(\sqrt{s})\times\epsilon_{e^+e^-\to X}(\sqrt{s})\times\sigma^{\rm obs}(\sqrt{s}), \quad (1)$$

where X denotes some final state produced in e^+e^- annihilation, $N^{\rm obs}_{e^+e^-\to X}$ is the number of events observed, $\epsilon_{e^+e^-\to X}$ is the detection efficiency for $e^+e^-\to X$, L is the integrated luminosity and $\sigma^{\rm obs}(\sqrt{s})$ is the observed production cross section for the process $e^+e^-\to X$ at center-of-mass energy $\sqrt{s}$.

To systematically study the properties of the production and decays of ψ(3770) and D mesons, a data set was taken at $\sqrt{s}$ =3.773 GeV, with the BESIII detector at the BEPCII, from January 2010 to May 2011. So far, this data set is the world's largest e^+e^- collision data set taken around the ψ(3770) resonance peak. In order to estimate the continuum contribution in studies of the resonance decays, another data set was taken in 2009 at $\sqrt{s}$=3.650 GeV, which is far away from the resonance peak. The data taken at $\sqrt{s}$=3.773 GeV was accumulated in different periods of BESIII running; the first part was taken from January 2010 to June 2010 and the second part was taken from December 2010 to May 2011. For convenience in the following, we call the data taken at $\sqrt{s}$= 3.650 GeV the continuum data, and call the two parts of the data taken at $\sqrt{s}$= 3.773 GeV ψ(3770) data A and ψ(3770) data B, respectively.

In this paper, we present the measurements of the integrated luminosities of the data sets taken at $\sqrt{s}$=3.650 and 3.773 GeV by analyzing the large angle Bhabha scattering events.

2 BESIII detector

The BESIII detector and the BEPCII collider [1] are major upgrades of the BESII detector and the BEPC collider [2]. The designed peak luminosity of the double-ring e^+e^- collider, BEPCII, is 10^{33} cm^{-2}·s^{-1} at a beam current of 0.93 A. The peak luminosity at $\sqrt{s}$=3.773 GeV reached 0.65×10^{33} cm^{-2}·s^{-1} in April 2011 during the ψ(3770) data taking. The BESIII detector, which has a geometrical acceptance of 93% of 4π, consists of the following main components: 1) a small-celled, helium-based main draft chamber (MDC) with 43 layers. The average single wire resolution is 135 μm, and the momentum resolution for 1 GeV/c charged particles in a 1 T magnetic field is 0.5%; 2) an electromagnetic calorimeter (EMC) made of 6240 CsI(Tl) crystals arranged in a cylindrical shape (barrel) plus two endcaps. For 1.0 GeV photons, the energy resolution is 2.5% in the barrel and 5% in the endcaps, and the position resolution is 6 mm in the barrel and 9 mm in the endcaps; 3) a Time-Of-Flight system (TOF) for particle identification composed of a barrel and two endcaps. The barrel part is made of two layers, each layer consisting of 88 pieces of 5 cm thick, 2.4 m long plastic scintillator. Each endcap consists of 96 fan-shaped, 5 cm thick, plastic scintillators. The time resolution is 80 ps in the barrel, and 110 ps in the endcaps, corresponding to a 2σK/π separation for momenta up to about 1.0 GeV/c; 4) a muon chamber system (MUC) made of 1600 m^2 of Resistive Plate Chambers (RPC) arranged in 9 layers in the barrel and 8 layers in the endcaps and incorporated in the return yoke of the superconducting magnet. The position resolution is about 2 cm.

3 Method

In principle, any QED process can be used to measure the integrated luminosity of the data set using

$$L(\sqrt{s})=\frac{N^{\rm obs}_{\rm QED}(\sqrt{s})\times(1-\eta)}{\sigma_{\rm QED}(\sqrt{s})\times\epsilon\times\epsilon^{\rm trig}_{\rm e^+e^-}}, \qquad (2)$$

where $N^{\rm obs}_{\rm QED}$ is the observed number of events of the final state in question, $\sigma_{\rm QED}$ is the production cross section, which can be determined by theoretical calculation, ϵ is the detection efficiency, η is the contamination ratio and $\epsilon^{\rm trig}_{\rm e^+e^-}$ is the trigger efficiency for collecting the QED process in the on-line data acquisition.

Usually, the processes $e^+e^-\rightarrow(\gamma)e^+e^-$, $e^+e^-\rightarrow(\gamma)\gamma\gamma$ and $e^+e^-\rightarrow(\gamma)\mu^+\mu^-$ are used to measure the integrated luminosity of the data because of their simpler final state topologies, larger production cross sections, higher detection efficiencies, as well as more precise expected cross sections available from theory. In this work, the large angle Bhabha scattering events of $e^+e^-\rightarrow(\gamma)e^+e^-$ are adopted. Throughout the paper, the symbol of "(γ)" denotes the possible photon (s) produced due to Initial State Radiation or Final State Radiation.

4 Luminosity measurement

4.1 Event selection

In order to select candidate Bhabha events, it is required that there should be only two good charged tracks, with total charge zero, which are reconstructed in the MDC. Each track must originate from the interaction region $R_{xy}<$ 1 cm and $|V_z|<$5 cm, where R_{xy} and $|V_z|$ are the points of closest approach relative to the collision point in the xy-plane and in the z direction, respectively. Furthermore, to ensure that the candidate charged track hits the barrel of the EMC, we require that the polar angle θ of the charged track satisfies $|\cos\theta|<$ 0.80.

Figure 1 shows the energy deposited in the EMC ($E_{\rm EMC}$) for the good charged tracks of events satisfying the above selection criteria, where the dots with red error bars are the continuum data, the yellow histogram is $e^+e^-\rightarrow(\gamma)e^+e^-$ Monte Carlo events and the light green histogram is $e^+e^-\rightarrow(\gamma)\mu^+\mu^-$ Monte Carlo events. From the figure it can be seen that the requirement

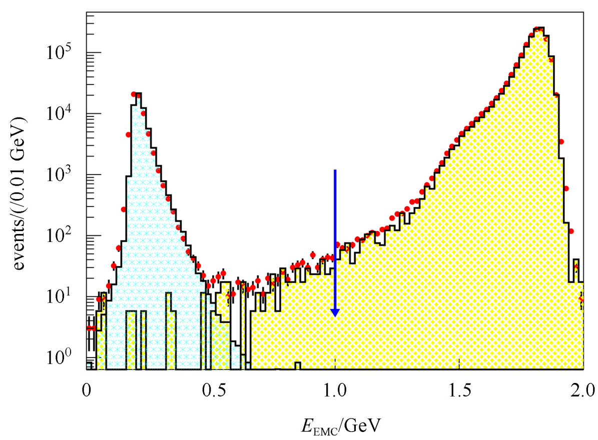

Fig. 1. The distributions of the energy deposited in the EMC from the charged tracks associated with the selected events. The dots with red error bars are the continuum data, the yellow histogram is $e^+e^-\rightarrow(\gamma)e^+e^-$ Monte Carlo events and the light green histogram is $e^+e^-\rightarrow(\gamma)\mu^+\mu^-$ Monte Carlo events.

$E_{\rm EMC}$ > 1.0 GeV can cleanly separate the $e^+e^- \to (\gamma)\mu^+\mu^-$ events from the Bhabha scattering events. To further remove background from cosmic rays, the momentum of at least one of the two charged tracks in the candidate Bhabha events should be less than $E_{\rm b}+$ 0.15 GeV, where $E_{\rm b}$ is the calibrated beam energy.

After applying the above selection criteria, the accepted events are mostly Bhabha scattering events. But there may still be a small amount of background from $e^+e^- \to (\gamma)J/\psi$, $e^+e^- \to (\gamma)\psi(3686) \to (\gamma)J/\psi X$ and $e^+e^- \to \psi(3770) \to (\gamma)J/\psi X$ ($J/\psi \to e^+e^-$ and $X=\pi^0\pi^0$, η, π^0 or $\gamma\gamma$). In order to remove these background events, the sum of the momenta of the two good charged tracks is required to be greater than $0.9\times E_{\rm cm}$. The remaining contamination from these background sources is estimated by Monte Carlo simulation, which will be discussed in Section 4.3.

4.2 Data analysis

The two oppositely charged tracks in the candidate Bhabha scattering events are bent in the magnetic field, so the positions of their two shower clusters in the xy-plane of the EMC are not back-to-back. To determine the observed number of Bhabha scattering events, we use the difference of the azimuthal angles of the two clusters in the EMC, which is defined as $\delta\phi=|\phi_1-\phi_2|-180°$ in degrees, where ϕ_1 and ϕ_2 are the azimuthal angles of the two clusters in the EMC. Fig. 2 shows the $\delta\phi$ distribution of the candidate Bhabha scattering events selected from the continuum data.

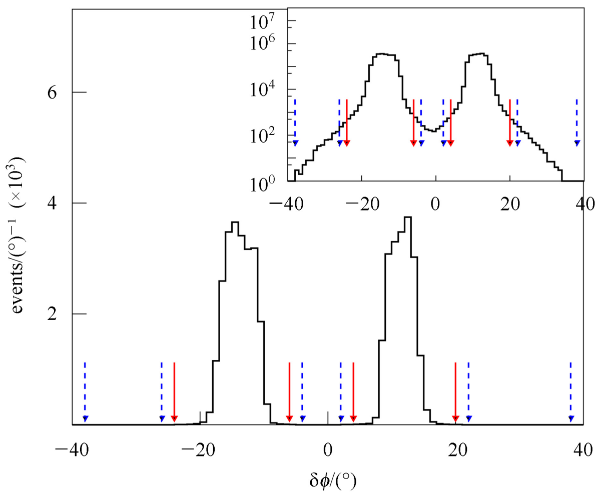

Fig. 2. The distribution of $\delta\phi$ ($\delta\phi=|\phi_1-\phi_2|-180°$) for the selected e^+ and e^- tracks. The main part and the inset are shown with linear and logarithmic scale, respectively.

In the figure, the events in the "signal" regions between the red arrows are taken as the signal events, while the ones in the "sideband" regions between the blue arrows are used to estimate the background in the $\delta\phi$ "signal" region. After subtracting the scaled number of the events in the sideband region from the number of events in the signal region, we obtain the numbers of the Bhabha scattering events observed from data, which are listed in the second row of Table 1.

4.3 Background estimation

For the accepted Bhabha scattering events, there may still be some residual background from $e^+e^- \to (\gamma)J/\psi$, $e^+e^- \to (\gamma)\psi(3686) \to (\gamma)J/\psi X$ and $e^+e^- \to \psi(3770) \to (\gamma)J/\psi X$ ($J/\psi \to e^+e^-$ and $X=\pi^0\pi^0$, η, π^0 or $\gamma\gamma$), as well as some other hadronic decay processes. These are estimated by analyzing the Monte Carlo events, including 16.5 M $e^+e^- \to (\gamma)J/\psi$, 51 M $e^+e^- \to (\gamma)\psi(3686)$, 198 M $e^+e^- \to \psi(3770) \to D\bar{D}$, 15 M $e^+e^- \to \psi(3770) \to$ non-$D\bar{D}$, and 183 M $e^+e^- \to$ continuum light hadron events. Detailed analysis gives the contamination rates to be $\eta=1.7\times10^{-5}$ and 1.7×10^{-4} for the candidate Bhabha scattering events selected from the continuum data and the $\psi(3770)$ data, respectively.

4.4 Detection efficiency for $e^+e^- \to (\gamma)e^+e^-$

To determine the detection efficiencies for the Bhabha scattering events, we generated 400000 $e^+e^- \to (\gamma)e^+e^-$ Monte Carlo events with the Babayaga generator [3], within the polar angle range of $|\cos\theta| < 0.83$ at $\sqrt{s}=$ 3.650 and 3.773 GeV, where θ is the polar angle for the e^+ and e^-. By analyzing these Monte Carlo events with the same selection criteria as the data analysis, we obtained the detection efficiencies for $e^+e^- \to (\gamma)e^+e^-$ at $\sqrt{s}$=3.650 and 3.773 GeV, which are summarized in the fourth row of Table 1.

4.5 Integrated luminosities

Inserting the numbers of observed Bhabha scattering events, the detection efficiencies for $e^+e^- \to (\gamma)e^+e^-$ obtained by the Monte Carlo simulation, the trigger efficiency and the visible cross sections within the polar angle range of $|\cos\theta| < 0.83$ in Eq. (2), we determine the integrated luminosities of the continuum data, the $\psi(3770)$ data A and the $\psi(3770)$ data B to be (44.49±0.02±0.44) pb^{-1}, (927.67±0.10±9.28) pb^{-1} and (1989.27±0.15±19.89) pb^{-1}, respectively, where the first errors are statistical and the second are systematic and discussed in the next section. The total luminosity of the $\psi(3770)$ data is (2916.94±0.18±29.17) pb^{-1}. Here, systematic uncertainties are completely correlated between the two parts of the data, and thus are added linearly when they are combined. Here, for the data sets used in the analysis, the trigger efficiency for collecting $e^+e^- \to (\gamma)e^+e^-$ events was determined to be $\epsilon^{\rm trig}_{e^+e^-}=100\%$ with the statistical error being less than 0.1% [4]. The numbers used in the luminosity measurements are summarized in Table 1.

Table 1. Summary of the numbers used in the determination of the luminosities, where $N^{\rm obs}_{\rm e^+e^-\to(\gamma)e^+e^-}$ is the number of candidate Bhabha scattering events selected from the data, ϵ is the detection efficiency, σ is the visible cross section for the Bhabha scattering events and L represents the integrated luminosity.

samples	ψ(3770) data A	ψ(3770) data B	continuum data
$N^{\rm obs}_{\rm e^+e^-\to(\gamma)e^+e^-}$ $(\times 10^4)$	8412.9±0.9	18140.3±1.3	432.0±0.2
η $(\times 10^{-4})$	1.7	1.7	0.17
ϵ (%)	61.28	61.62	61.47
σ/nb	147.9599	147.9599	157.9393
L/pb^{-1}	927.67±0.10±9.28	1989.27±0.15±19.89	44.49±0.02±0.44

4.6 Systematic error

In the measurements of the integrated luminosities, the systematic errors arise from the uncertainties associated with the Bhabha event selection, the Monte Carlo statistics, the background estimation, the signal region selection, the trigger efficiency and the generator.

In order to estimate the systematic uncertainty due to the $\cos\theta$ requirement, we also determine the integrated luminosities with the selection requirements of $|\cos\theta|<$ 0.75 and 0.70. The differences from the standard selection of $|\cos\theta|<0.80$ are all less than 0.5% for both the continuum data and ψ(3770) data. To be conservative, we take 0.75% as the systematic error due to the $\cos\theta$ selection in this work. The systematic uncertainty due to the MDC measurement information, which includes the uncertainties due to the MDC tracking efficiency and the momentum requirement, is determined to be 0.3% by comparing the integrated luminosities measured with and without the MDC measurement information. The systematic uncertainty due to the $E_{\rm EMC}$ energy selection requirements is determined to be 0.2%, by comparing the $E_{\rm EMC}$ distributions of the data and Monte Carlo events. The uncertainty from the EMC cluster reconstruction is determined to be 0.03% by comparing the efficiencies of the data and the Monte Carlo events.

The uncertainty from the Monte Carlo statistics is 0.1%. The uncertainty in the background subtraction is negligible. The uncertainty due to the $\delta\phi$ signal region selection is estimated to be 0.01% by comparing the integrated luminosities measured with different signal regions. In these measurements, we use the trigger efficiency for collecting $\rm e^+e^-\to(\gamma)e^+e^-$ events of $\epsilon^{\rm trig}_{\rm e^+e^-}=100\%$ with the statistical error being less than 0.1% [4]. Therefore, we take 0.1% as the systematic uncertainty due to trigger efficiency. The uncertainty due to the Bhabha generator is 0.5%, which is cited from Ref. [3].

Table 2 summarizes the above systematic uncertainties in the luminosity measurement. The total systematic error is determined to be 1.0% by adding these uncertainties in quadrature.

Table 2. The relative systematic uncertainties in the luminosity measurement.

sources	$\Delta^{\rm sys}$ (%)
$\lvert\cos\theta\rvert<0.80$	0.75
$E^{\rm e^+}_{\rm EMC}>1$ GeV	0.2
$E^{\rm e^-}_{\rm EMC}>1$ GeV	0.2
MDC information	0.3
EMC cluster reconstruction	0.03
Monte Carlo statistics	0.1
background estimation	0.0
signal region selection ($\delta\phi$)	0.01
trigger efficiency [4]	0.1
generator [3]	0.5
total	1.0

5 Summary

By analyzing the Bhabha scattering events, we measure the integrated luminosities of the data taken with the BESIII detector at $\sqrt{s}$=3.650 and 3.773 GeV to be (44.49±0.02±0.44) pb^{-1} and (2916.94±0.18±29.17) pb^{-1}, respectively. These luminosities can be used for normalization in studies of ψ(3770) production and decays, as well as in studies of D meson production and decays.

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